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In models where the ultra-high energy cosmic ray problem is solved by top-down scenarios, a significant flux of ultra-high energy neutralinos is predicted. We calculate the number of events expected from such particles in future experiments such as EUSO or OWL. We show that by using the Earth as a filter, showers generated by neutralinos can be separated from neutrino generated showers. We find that for many models, observable rates are expected.

11.30.Pb, 14.80.Ly, 95.85.Ry, 96.40.De, 96.40.Pq, 96.40.Tv

I. INTRODUCTION

Cosmic ray observations have determined that the spectrum of the highest energy cosmic rays extends beyond 10^{20} eV [1]. Observations have also indicated that the highest energy spectrum is dominated by protons rather than photons [2]. Above $\sim 5 \times 10^{19}$ eV, protons can interact with cosmic background photons at the Δ-resonance generating pions. Above this energy, called the GZK (Greisen-Zatsepin-Kuzmin) cutoff [3], the proton energy loss length is near 50 Mpc, thus requiring semi-local sources to produce the observed flux. The lack of any such known sources has spawned a great deal of speculation as to the origin of these particles. A common class of models, called top-down scenarios, involve supermassive particles which decay or annihilate generating the highest energy cosmic rays [4,5].

The decay of superheavy particles has been studied in some detail [6–10]. In particular, it has been demonstrated that a significant amount of the initial energy of such a particle can be emitted in the form of ultra-high energy supersymmetric particles [6,9,10]. In most models, the lightest supersymmetric particle is a neutralino. This neutralino, weakly interacting and stable by virtue of $R-$parity, can travel cosmological distances without absorption or scattering. In this paper, we discuss the prospects for observing ultra-high energy cosmic neutralinos in future very large area, satellite-borne air shower experiments.

II. ULTRA-HIGH ENERGY FRAGMENTATION TO NEUTRALINOS

In the general framework of top-down scenarios, one has to consider the decay of super-heavy X particles with a mass of the order of 10^{21} to 10^{25} eV, and a lifetime comparable to or longer than the age of the universe. Such a long lifetime can be ensured by "storing" the $X-$particles in cosmological defects, which can survive into the present epoch [4,11]. Alternatively, free $X-$particles might be long–lived since their decay is suppressed, e.g. by (approximate) symmetries [12]. For a review of different candidates, see [5]. Such particles could be produced in the very early times of the universe, e.g. at the end of inflation [13]. The typical decay modes of the X particles are generally unknown and/or quite model dependent. Yet, according to the desert hypothesis,[†] there should be no energy scale related to new physics between the scale of SUSY breaking ($\sim$ 1 TeV) and the GUT scale. In such a case, the X particles should decay into N "known" particles of the MSSM, and usual particle physics allows us to study in detail the shower generated by the primary products of the initial X decay. One can thus derive the final spectra of stable particles for any primary decay channel of the X particle.

A detailed computation of the spectra of stable particles (protons, photons, neutralino LSPs, electrons and neutrinos of the three species) obtained in such decay showers has been described in [9,14]. We assume that X decays are CP-symmetric, i.e. we assume equal fluxes of particles and antiparticles of a given species. We recall here that at the energies we are considering, it is necessary to take into account all the gauge couplings of the MSSM; indeed, at the scale of unification, they are all of the same strength, so that electroweak (and some Yukawa) interactions turn to be as relevant as the QCD ones. The perturbative part of the shower was computed by solving numerically the complete set of DGLAP evolution equations [14] for the relevant fragmentation functions of the MSSM. We carefully modeled the decays of unstable particles with mass near $M_{\mathrm{SUSY}} \sim 1$ TeV, as well as the hadronization process at the GeV scale for light quarks and gluons. Some sample spectra are shown in Fig. 1. Here we have conservatively assumed that X particles have an overdensity of 10^5 in the vicinity of our galaxy, which minimizes the expected neutralino flux (all

[†] The so–called desert hypothesis is often made in SUSY models to protect the unification of couplings at $\sim 10^{25}$ eV obtained through the RGE running of couplings in the Minimal Supersymmetric Standard Model (MSSM).

scenarios are normalized to match the proton spectrum to the highest energy cosmic ray observations). A similar overdensity is in fact expected [7] if the X particles constitute a sizable fraction of the (non–baryonic) Dark Matter in the Universe.

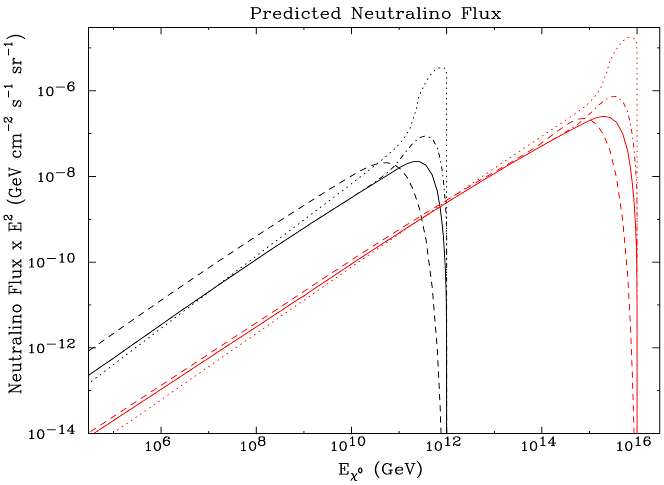

FIG. 1. The spectrum of neutralino LSP's predicted for the decay of superheavy particles with mass $M_X = 2 \cdot 10^{21}$ eV (darker) and $M_X = 2 \cdot 10^{25}$ eV (lighter) normalized by the proton spectrum to the ultra-high energy cosmic ray flux. The distribution of sources used includes an overdensity factor of 10^5 within 20 kpc of the galaxy. For an isotropic distribution, the spectrum is enhanced by up to a factor of 15. Spectra are shown for quark+antiquark (solid), quark+squark (dot-dash), $SU(2)$ doublet lepton+slepton (dots) and 5 quark+5 squark (dashes) initial states. Note that for the case of $M_X = 2 \cdot 10^{21}$ eV decays, the spectrum peaks in the energy range most accessible to air shower experiments.

III. SIGNATURES OF ULTRA-HIGH ENERGY NEUTRALINOS

Ultra–relativistic neutralinos interact with quarks by $t-$channel Z and $W^{\pm}$ exchange, as well as by the exchange of squarks in the $s-$ or $u-$channel. These interactions yield a neutralino or chargino which quickly decays to the lightest neutralino (except, perhaps, in the case of near–degenerate masses). Either interaction generates a shower which can be observed by air shower experiments.

The background for this signal consists of showers generated by ultra-high energy cosmic neutrinos. The neutrino interaction length becomes comparable to the radius of the earth around 10^5 GeV. By 10^9 GeV, only about one out of 1000 neutrinos passes through the Earth without interaction (see figure 2). A neutralino, however, depending on the choice of SUSY parameters, will have a different interaction cross section and, therefore, different absorption properties. The size of this cross section depends sensitively on the neutralino eigenstate, which in general is a composition of bino, wino and neutral higgsinos. A wino– or higgsino–like neutralino has couplings to W and/or Z bosons that resemble or even exceed those of neutrinos. In contrast, a bino–like neutralino has very small couplings to gauge boson, because its superpartner, the $U(1)_Y$ gauge boson, does not couple to other gauge bosons. The couplings of bino–like neutralinos to squarks are of full $U(1)_Y$ gauge strength, but squark searches at the Tevatron [15] tell us that first and second generation squarks must be at least three times heavier than W bosons. Note also that models with radiative breaking of the electroweak gauge symmetry prefer the lightest neutralino to be bino–like in most of parameter space [16]. Typical parameter choices therefore predict neutralino-nucleon cross sections one or two orders of magnitude smaller than neutrino-nucleon cross sections [6]. With a significantly smaller cross section, very high energy cosmic neutralinos may travel through the Earth producing upgoing events at much higher energies than neutrinos. Upgoing showers with energy above 100 PeV or so would be a smoking gun for cosmic neutralinos.

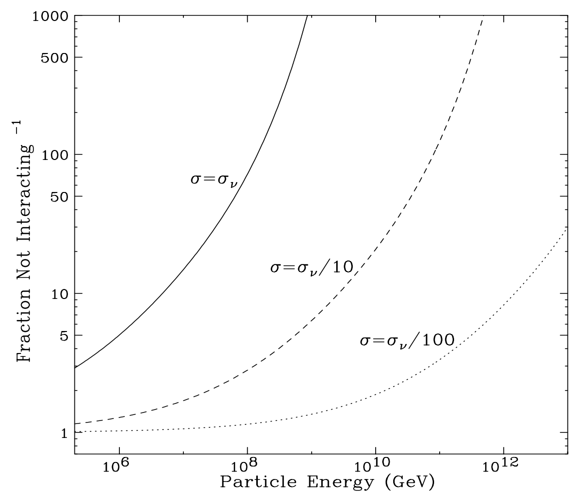

FIG. 2. The fraction of neutrinos or neutralinos which pass through the Earth (zenith angle less than 85 degrees) as a function of energy. Results are shown for particles with total cross sections with nucleons equal to that for neutrinos as well as for particles with cross sections ten and one hundred times smaller. Regeneration effects are not included (see section IV).

Furthermore, by virtue of R-parity, neutralinos will generate less energetic neutralinos in each interaction, thus not depleting their number. Tau neutrinos also display this property [17], but not as dramatically. The difference comes from the fact that high energy tau leptons lose energy in propagation whereas charginos decay quickly enough to lose very little energy in propagation. Also, generally, a larger fraction of a decaying chargino's energy goes into the resulting neutralinos than a decaying tau's energy goes into the new tau neutrino. Together, these effects indicate that tau regeneration is largely ineffective above about 10^8 GeV. On the other hand, for even moderately smaller neutralino cross sections, the Earth can remain effectively transparent to cosmic neutralinos at much higher energies.

IV. PROSPECTS FOR DETECTION IN AIR SHOWER EXPERIMENTS

The flux of very high energy neutralinos from top-down scenarios can be calculated assuming that this is the mechanism which generates the highest energy cosmic rays [4,8,18]. Given a sufficient cosmic flux, these neutralinos may be detected in future air shower experiments. The greater challenge, however, is not merely observing the showers generated in neutralino interactions but in differentiating these cosmic neutralinos from neutrinos.

We have calculated the number of neutralino events predicted for a variety of top-down models associated with the highest energy cosmic rays in a future experiment such as EUSO [19] or OWL [20]. EUSO and OWL are proposed satellite experiments which observe fluorescence in the Earth's atmosphere generated in very high energy showers. Such experiments are expected to observe on the order of 150,000 square kilometers of surface area on the Earth. Particles which pass through the Earth can interact in the shallow Earth or atmosphere generating upgoing showers observable by fluorescence or Cerenkov radiation. Ultra-high energy showers reach a maximum near a slant depth of 850 g/cm^2, corresponding to a depth of 8.5 meters in water. Including the effective slant depth of the lower atmosphere extends this to ~ 0.015 km, thus providing a water equivalent effective volume of $\sim 150,000 \times 0.015 \sim 2250$ cubic kilometers, a truly enormous volume. Such an experiment will be capable of measuring both the energy and the direction of an observed particle. We consider events only coming from 5 degrees or more below the zenith.

Table I shows these event rates for two choices of energy threshold, $E_{\chi^0} \geq 1$ EeV and 100 EeV. This choice reflects both the experimental threshold which may apply and a cut in energy to limit the number of background events from high energy neutrinos passing through the Earth. Tau neutrinos do not regenerate efficiently at these energies (they lose the majority of their energy during tau propagation), thus these backgrounds can be controlled. At 1 EeV less than .1 % of neutrinos pass through the Earth without interaction. Furthermore, even much more energetic tau neutrinos, say of 10^3 EeV, emerge from the Earth with energy above 1 EeV only one out of 2000 times. Of course, the choice of a 100 EeV threshold is even more effective. Regarding the energy threshold which can be achieved experimentally, it has been argued that for upgoing events, the threshold could be as small as a PeV [21].

The angular distribution of events depends strongly on the neutralino-nucleon cross section. For the choice of $\sigma = \sigma_\nu/100$, the angular distribution is expected to be largely flat. For a larger cross section, the events can begin to cluster near the horizon. To avoid confusing near-horizontal neutralino events with experimental backgrounds, we consider only events at least 5 degrees below the horizon.

The rates shown in table I are for a variety of initial fragmentation states and distributions. For a full description of these models, see our previous paper [18]. We note that the neutralino signal is more sensitive to the primary X decay mode than the neutrino signal analyzed in [18] is. Not surprisingly, scenarios with (at least) one superparticle in the primary decay produce a higher

$E_{\chi^0} \geq 1\,\mathrm{EeV}$	$\sigma_{\chi^0} = \sigma_\nu/10$	$\sigma_{\chi^0} = \sigma_\nu/100$
$q\bar{q}$, 10^{21} eV, Galactic	1.86	0.196
$q\tilde{q}$, 10^{21} eV, Galactic	2.96	0.306
$5 \times q\tilde{q}$, 10^{21} eV, Galactic	4.05	0.436
$l\tilde{l}$, 10^{21} eV, Galactic	28.0	2.81
$q\bar{q}$, 10^{25} eV, Galactic	0.187	0.0189
$q\tilde{q}$, 10^{25} eV, Galactic	0.213	0.0216
$5 \times q\tilde{q}$, 10^{25} eV, Galactic	0.213	0.0216
$l\tilde{l}$, 10^{25} eV, Galactic	0.615	0.0617
$q\bar{q}$, 10^{21} eV, Homogeneous	27.9	2.94
$q\tilde{q}$, 10^{21} eV, Homogeneous	44.4	4.56
$5 \times q\tilde{q}$, 10^{21} eV, Homogeneous	60.8	6.54
$l\tilde{l}$, 10^{21} eV, Homogeneous	420.0	42.15
$q\bar{q}$, 10^{25} eV, Homogeneous	2.81	0.284
$q\tilde{q}$, 10^{25} eV, Homogeneous	3.20	0.324
$5 \times q\tilde{q}$, 10^{25} eV, Homogeneous	3.20	0.324
$l\tilde{l}$, 10^{25} eV, Homogeneous	9.23	0.926
$E_{\chi^0} \geq 100\,\mathrm{EeV}$	$\sigma_{\chi^0} = \sigma_\nu/10$	$\sigma_{\chi^0} = \sigma_\nu/100$
$q\bar{q}$, 10^{21} eV, Galactic	0.0976	0.0344
$q\tilde{q}$, 10^{21} eV, Galactic	0.391	0.122
$5 \times q\tilde{q}$, 10^{21} eV, Galactic	0.0161	0.00716
$l\tilde{l}$, 10^{21} eV, Galactic	10.1	2.38
$q\bar{q}$, 10^{25} eV, Galactic	0.0946	0.0143
$q\tilde{q}$, 10^{25} eV, Galactic	0.116	0.0169
$5 \times q\tilde{q}$, 10^{25} eV, Galactic	0.103	0.0159
$l\tilde{l}$, 10^{25} eV, Galactic	0.435	0.0576
$q\bar{q}$, 10^{21} eV, Homogeneous	1.46	0.516
$q\tilde{q}$, 10^{21} eV, Homogeneous	5.87	1.83
$5 \times q\tilde{q}$, 10^{21} eV, Homogeneous	0.242	0.107
$l\tilde{l}$, 10^{21} eV, Homogeneous	151.5	35.7
$q\bar{q}$, 10^{25} eV, Homogeneous	1.42	0.215
$q\tilde{q}$, 10^{25} eV, Homogeneous	1.74	0.254
$5 \times q\tilde{q}$, 10^{25} eV, Homogeneous	1.55	0.239
$l\tilde{l}$, 10^{25} eV, Homogeneous	6.53	0.864

TABLE I. Neutralino event rates per year in top-down scenarios in a large area air shower experiment such as EUSO or OWL, with effective volume $\simeq$ 2250 cubic kilometers (water equivalent). Rates are shown for two choices of neutralino-nucleon cross sections, two choices of energy threshold and several top-down models. At the energies considered, there is very little neutrino background for upgoing events (see text).

neutralino flux than models where X only decays into quarks. Moreover, leptonic X decays increase the predicted neutralino flux by another order of magnitude, since in this case relatively few protons are produced, leading to a higher source density required to explain the observed UHECR events. On the other hand, chosing $M_X = 2 \cdot 10^{25}$ eV rather than $2 \cdot 10^{21}$ eV significantly reduces the predicted flux. Note, however, that in this case X decays can only describe the UHECR flux above $\sim 10^{20}$ eV [18]; events at a few times 10^{19} eV then have to be produced by an as yet unknown source.

V. CONCLUSIONS

The cosmic neutralino flux predicted in top-down scenarios could possibly provide an interesting test of both supersymmetry and GUT scale particle physics. To identify any showers generated in future experiments as being generated by cosmic neutralinos, they will need to occur at energies and from directions at which neutrinos would be absorbed by the Earth. We have calculated the event rates for a variety of such models for a large area air shower experiment such as OWL or EUSO. We find that for many scenarios, the event rate is large enough for observation. Moreover, the neutralino event rate turns out to be a far more sensitive probe of details of the model than the flux of neutrinos with energy exceeding ~ 1 PeV [18].

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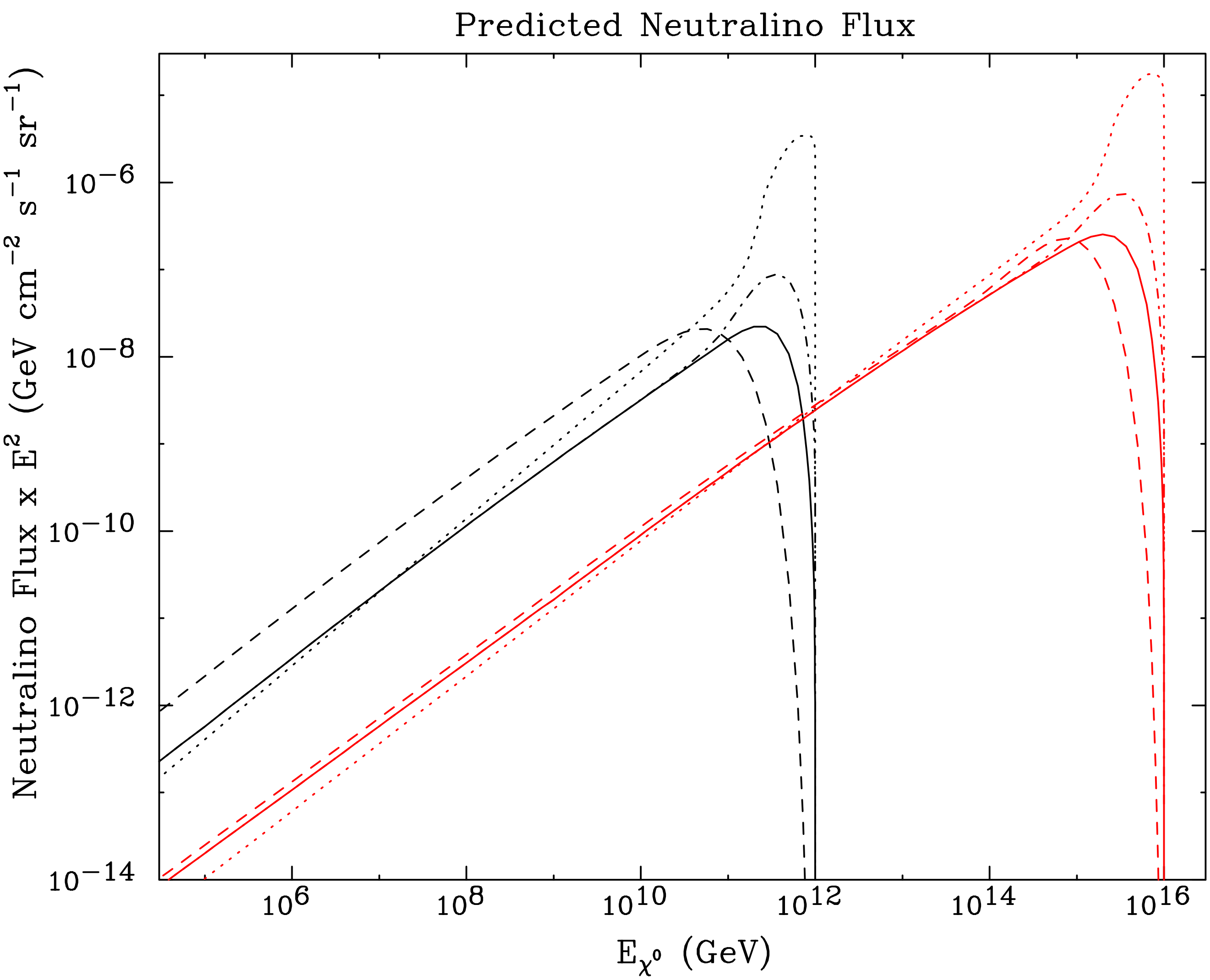
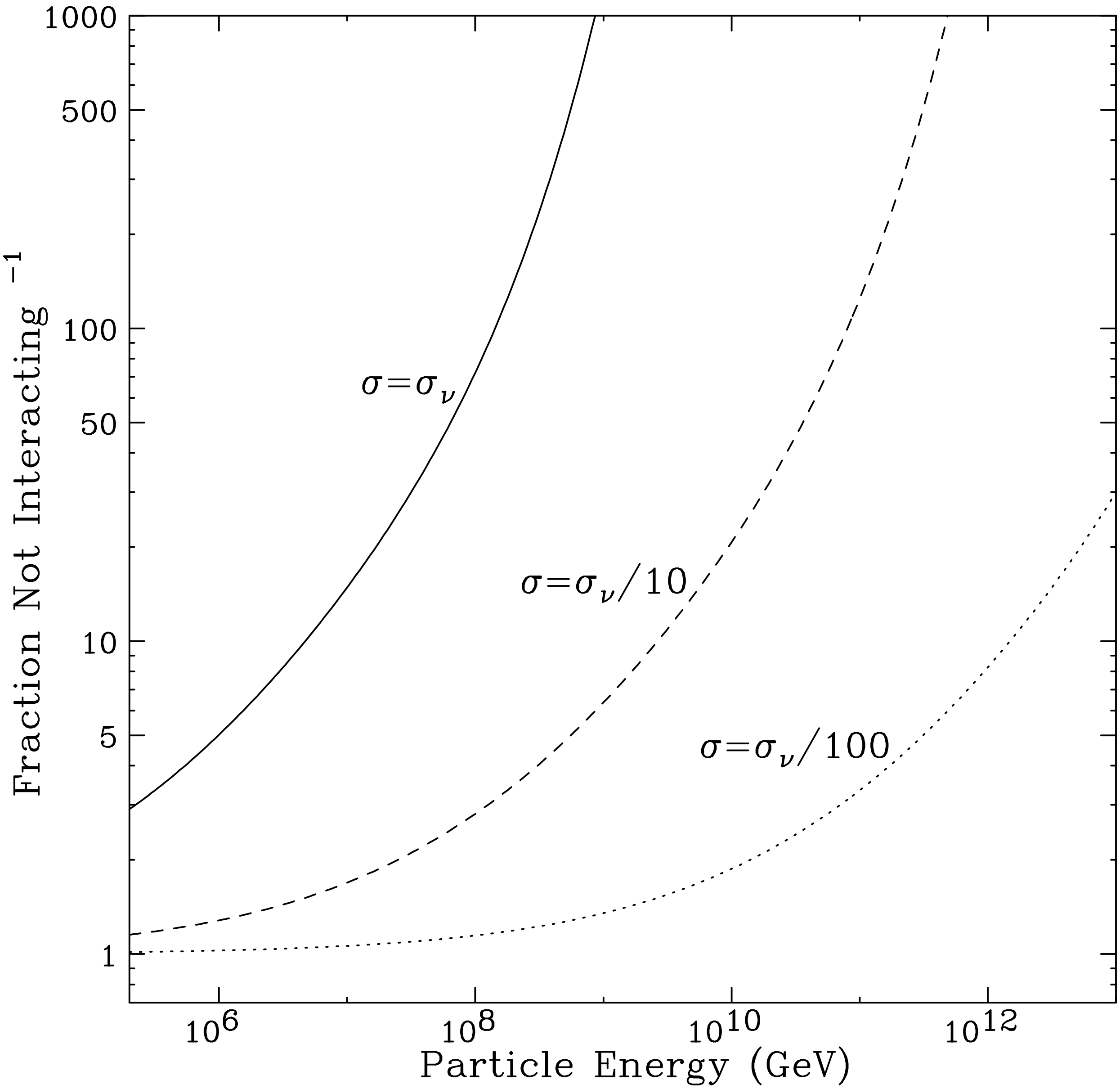


Predicted Neutralino Flux
Neutralino Flux x E^2 (GeV cm^{-2} s^{-1} sr^{-1})
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}
10^{16}
E_{χ^0} (GeV)



1000
500
100
50
10
5
1
10^6
10^8
10^{10}
10^{12}
Particle Energy (GeV)
Fraction Not Interacting $^{-1}$
$\sigma=\sigma_\nu$
$\sigma=\sigma_\nu/10$
$\sigma=\sigma_\nu/100$